Orbit Correction Implementation at CEBAF*

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Abstract

CEBAF has recently performed automated beam orbit control in real time. This effort was achieved by exploiting the capabilities of the TACL control system, using the newly implemented STAR network, which easily yielded the required data transfer density needed. Also involved in this effort was the On-Line Envelope code OLE, which provided first-order transfer matrices that reflected the current machine optics. These tools made the implementation of the specific orbit-correction algorithms easier and increased reliability. The implemented algorithms include beamthreading, orbit-locks with 2 correctors/2 monitors, most-effective corrector, and *n*-corrector/*n*-monitor correction.

I. INTRODUCTION

The CEBAF superconducting accelerator[1] is a recirculating cw electron linac consisting of a 45 MeV injector linac, two 0.4 GeV main linacs, a recirculator, and a beam switchyard. Each beam can be recirculated up to five times for a final energy of 4 GeV. In both arcs, beamlines tuned to specific energies transport the different-energy beams between linacs; at the end of each arc, the beams are recombined and made collinear for reinjection and further acceleration. There are 1400 correction magnets and 550 beam position monitor devices.

The large magnitude of correction elements at CEBAF requires automated beam orbit control for proper accelerator operation. A requirement therefore exists to develop algorithms which will automatically correct beam position and optical parameters. Tools have been developed to greatly assist in this development. CEBAF has recently implemented the STAR network protocol, which has vastly improved the data transfer speed and ease of obtaining current operational values. A machine model has been developed, known as the On-Line Envelope (OLE), which uses real time magnet currents and RF cavity settings, computing ideal optics and transfer matrices. These values are delivered to the orbit correction applications by the STAR and reflect the current running state of the accelerator.

With the use of these tools, it is quite easy to implement various correction methods. CEBAF has just successfully completed the high-power and east arc tests, and some orbit correction techniques have been tested. This paper will discuss these methods, as well as others that have been implemented in code and are ready for real beam testing.

II. STAR DATA DIRECTOR

In TACL[2], the STAR[3] is a request-based entity responsible for signal data communications among applications. In general, signals represent readbacks and setpoints for hardware and software controls that are created in TACL logic sets. Although these signals are updated each logic cycle, the STAR communicates signal updates only for those requested by applications such as other logic sets, TACL display pages, and stand-alone simulations. Signal value changes are recorded and maintained in shared memory on the front-end computers, known as locals. When a signal is requested by an application, the STAR sends out a request to the logic set that owns the signal. After checking the shared memory on the front-end computer, the logic set sends the update to the STAR which, in turn, passes the data to the application originating the request.

In this scheme, stand-alone simulations (like OLE) operate like logic sets on front-end computers in that they write to shared memory, but the aspect that looks at shared memory and communicates with the STAR is managed by programs called spy programs. These programs use standard STAR protocols to communicate with the STAR, but they are customized to read the shared memory generated by the simulation and package the information into an acceptable signal format for the STAR.

Application programs, like orbit correction codes, attach to the STAR by a single function call. Data value setting and retrieval are accomplished by the use of other easy-to-use function calls. The STAR is implemented using Berkeley Sockets under TCP/IP protocol, which allows attachment from any other computer located on the network which are routable to the computer executing the STAR code. The STAR maintains a list of computers and valid users which have write permission—all other connections can only receive data. This feature allowed testing of application program execution and logical flow without the fear of contaminating data values and, possibly, consequential machine damage.

III. ON-LINE ENVELOPE

CEBAF originally developed the OLE[4] program, which quickly computes first-order machine Twiss parameters, in order to model and correct the beam envelope. The design goal of OLE was to develop a machine model which would use real-time machine settings, such as magnet currents and RF cavity amplitudes and phase, and generate beta functions and phase advance values at various points around the lattice, with updates taking less than one second to compute and post. With the combined use of efficient programming techniques and modern fast computers, this goal was easily achieved.

OLE starts the calculation by obtaining magnet optical strengths, obtained directly from the magnet LOGIC for each element, which develops the calculation based on beam

energy and excitation curves for that element. Also inputted are cavity amplitude and phase settings, obtained from the RF LOGIC. Initial alpha and beta values used are derived from emittance measurements and back-propagated to the beginning of the lattice for use by OLE.

OLE performs first-order optics calculations using 2 x 2 matrix formulation for calculating the machine beta function at a point, by the use of orthogonal trajectories:

$$\begin{pmatrix} X_1 & X_2 \\ X_1' & X_2' \end{pmatrix} = \begin{pmatrix} \sqrt{\beta}\cos\phi & \sqrt{\beta}\sin\phi \\ -\dfrac{\alpha}{\sqrt{\beta}}\cos\phi - \sqrt{\beta}\phi'\sin\phi & -\dfrac{\alpha}{\sqrt{\beta}}\sin\phi + \sqrt{\beta}\phi'\cos\phi \end{pmatrix}$$

where ϕ is the arbitrary initial phase angle, usually set to zero, and α and β are initial amplitude functions. Transfer matrices of the familiar form used for propagating (X X') are used for the above trajectories. The transfer matrix used for the accelerating cavities was developed at CEBAF and is basically a particle-tracing algorithm which numerically adjusts a model of the electric field, matching the energy gain measured in the RF controls system. The matrix contains focusing effects which the particles experience in the CEBAF cavities.

The Twiss parameters can be found by:

$$\beta = R_{11}^2 + R_{12}^2$$
$$\alpha = -R_{11}R_{21} - R_{12}R_{22}$$
$$\phi = \tan^{-1}\left(\frac{R_{12}}{R_{11}}\right)$$

These parameters can be used to produce transfer matrices of the familiar form:

$$M(s1,s2) = \begin{pmatrix} \sqrt{\dfrac{\beta_2}{\beta_1}}(\cos\Delta\phi + \alpha_1\sin\Delta\phi) & \sqrt{\beta_1\beta_2}\,\sin\Delta\phi \\ \dfrac{(1+\alpha_1\alpha_2)\sin\Delta\phi + (\alpha_2-\alpha_1)\cos\Delta\phi}{\sqrt{\beta_1\beta_2}} & \sqrt{\dfrac{\beta_1}{\beta_2}}(\cos\Delta\phi - \alpha_2\sin\Delta\phi) \end{pmatrix}$$
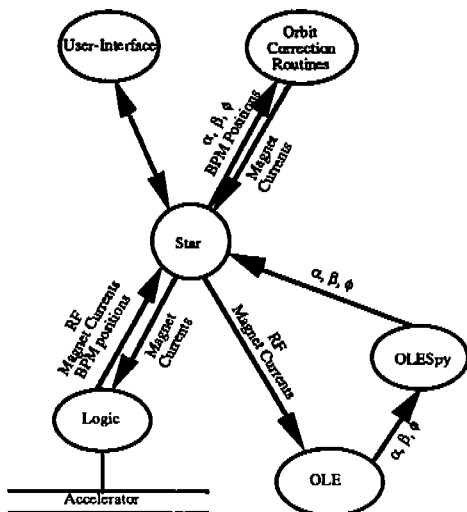

Figure 1. OLE-STAR Block Diagram

OLE constantly checks for changes in the magnet or RF values and recomputes new parameters when changes occur. The resulting Twiss parameters are posted on the STAR for use by all application programs via the OLEspy program (figure 2). The use of OLE results in a method of predicting orbit corrections for the current machine settings without user interaction, simplifying implementation and increasing reliability.

IV. ORBIT CORRECTION METHODS

Using the above tools made implementation of orbit correction algorithms very simple, allowing the person developing the code to concentrate mostly on the algorithm, not the implementation. Most orbit correction techniques read beam position monitor data, compute a correction, and set changes in corrector strengths. The STAR allows the global reading of various monitor data in one function call, passing back an array of values. Corrector strengths, in optical units as a function of energy and set current, are generated at the local computer level and are transferred by the STAR in an identical manner. Similarly, in one function call, Twiss parameters generated by OLE for all invoked corrector and monitors are delivered, and transfer matrices between elements are easily created.

CEBAF has recently attempted automatic steering for the first time. The first tested algorithm was beamthreading, which employs one corrector and one monitor, with the goal being to predict and correct the beam orbit. The algorithm implemented was to predict a kick which would locally correct the orbit at a downstream point:

$$\Delta K_1 = \frac{-\Delta X_{monitor}}{\sqrt{\beta_{corrector}}\sqrt{\beta_{monitor}}\sin(\phi_{monitor} - \phi_{corrector})}$$

The denominator is the M_{12} transfer matrix, which describes a downstream change in displacement from an upstream kick. OLE computations had been verified previously by comparing results with DIMAD, TRANSPORT, and PETROS simulation codes, and by predicting beam sizes through several quadrupoles and comparing with real beam emittance measurements. The other factors involved that were tested included the calibrations of the beam position monitors, which were determined from test stand data, and the computation of optical strength from magnet current and beam momentum measurement.

The beamthreading algorithm, as implemented, uses one monitor and one corrector and performs the correction, iterating if necessary, and then moves to the next corrector/monitor pair. This method, although slow, is simple and results in a properly zeroed orbit. It has the added advantage of easily testing the model against the real machine, as well as testing the monitor and corrector devices.

The above equation was applied in the spreader and arc section of the machine during the east arc commissioning tests, which were recently completed. The energy at this point

was 130 MeV, and the testing was performed using pulsed beam operation, using the beam position monitors in pulsed configuration. The results were very encouraging, with the achieved correction within 10 percent of zero position with one application.

With the success of the beamthreading method, the algorithm was expanded to use two correctors and two monitors. This effectively corrects the slope and displacement of the beam and will result in a beam with zero slope and zero displacement, and is known as an orbit lock. If one wishes to maintain a given orbit in an area of the machine, this method snapshots the initial beam position monitor readings and declares these values as the zero reference trajectory. Subsequent readings are subtracted from these values to find differences in position. The equation of the lock is of the form:

$$\begin{bmatrix} \sqrt{\beta_{c1}\beta_{m1}}\sin(\phi_{m1}-\phi_{c1}) & \sqrt{\beta_{c2}\beta_{m1}}\sin(\phi_{m1}-\phi_{c2}) \\ \sqrt{\beta_{c1}\beta_{m2}}\sin(\phi_{m2}-\phi_{c1}) & \sqrt{\beta_{c2}\beta_{m2}}\sin(\phi_{m2}-\phi_{c2}) \end{bmatrix} \begin{bmatrix} \Delta_{k1} \\ \Delta_{k2} \end{bmatrix} = -\begin{bmatrix} \Delta_{x1} \\ \Delta_{x2} \end{bmatrix}$$

This was employed in the region after the north linac immediately preceding the east arc spreader. The result obtained were that expected for this method, with the orbit returning back to the zero-defined trajectory after execution of the lock program. The program was made to execute when the orbit measured exceeded a set tolerance, which allowed the orbit downstream of the lock to remain stable regardless of the upstream orbit. This lock is desirable when one performs dispersion measurements in the spreader region while altering a parameter in the injector or linac, to maintain a constant trajectory preceding the spreader dipole.

The next natural extension of the above is to expand to many correctors and many monitors. For N correctors and N monitors, the equation takes the form of a square matrix as above with N equations which can be solved directly. For some cases occurring in the CEBAF arcs, there are more correctors than monitors. This results in an underdetermined equation system, which can be solved using singular-value decomposition. These correction methods have been coded but have not been tested with actual beam.

Other correction methods have been implemented, such as the Micado method (most-effective corrector), beam bumps, least squares correction of several correctors and several monitors, and entrance angle and displacement adjustment for multi-pass linac operation. These methods, however, have not yet been beam-tested.

To assist in the debugging of orbit correction methods, as well as other computer-assisted optics adjustments, a simulation reflecting the CEBAF lattice has been developed[4]. This simulation operates similarly to the OLE code, reading real-time magnetic strengths and RF parameters and computing a central trajectory orbit, with this orbit replacing the beam position monitor readings in the real machine. The orbit correction codes operate on the machine as designed and the simulation reacts to the corrections as

would real accelerated beam. Therefore, the codes can be thoroughly debugged and tested for proper operation before being put into service.

V. REFERENCES

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